

Open Research Online

The Open University's repository of research publications
and other research outputs

Isotopic composition of carbon and nitrogen in ureilitic fragments of the Almahata Sitta meteorite

Journal Item

How to cite:

Downes, H.; Abernethy, F. A. J.; Smith, C. L.; Ross, A. J.; Verchovsky, A. B.; Grady, M. M.; Jenniskens, P. and Shaddad, M. H. (2015). Isotopic composition of carbon and nitrogen in ureilitic fragments of the Almahata Sitta meteorite. *Meteoritics & Planetary Science*, 50(2) pp. 255–272.

For guidance on citations see [FAQs](#).

© 2015 The Meteoritical Society



<https://creativecommons.org/licenses/by-nc-nd/4.0/>

Version: Accepted Manuscript

Link(s) to article on publisher's website:
<http://dx.doi.org/doi:10.1111/maps.12413>

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online's data [policy](#) on reuse of materials please consult the policies page.

oro.open.ac.uk

Isotopic composition of carbon and nitrogen in ureilitic fragments of the Almahata Sitta meteorite

H. DOWNES^{1,2,3*}, F. A. J. ABERNETHY⁴, C. L. SMITH³, A. J. ROSS^{2,3,5}, A. B. VERCHOVSKY⁴,
M. M. GRADY⁴, P. JENNISKENS⁶, and M. H. SHADDAD⁷

¹Department of Earth and Planetary Sciences, Birkbeck University of London, Malet Street, London WC1E 7HX, UK

²UCL/Birkbeck Centre for Planetary Sciences, UCL, Gower Street, London WC1E 6BT, UK

³Department of Earth Sciences, Natural History Museum, Cromwell Road, London SW7 5BD, UK

⁴Department of Physical Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK

⁵Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK

⁶SETI Institute, Carl Sagan Centre, 189 Bernardo Avenue, Mountain View, California 94043, USA

⁷Department of Physics, University of Khartoum, PO Box 321, Khartoum 11115, Sudan

*Corresponding author. E-mail: h.downes@ucl.ac.uk

(Received 04 April 2014; revision accepted 13 November 2014)

Abstract—This study characterizes carbon and nitrogen abundances and isotopic compositions in ureilitic fragments of Almahata Sitta. Ureilites are carbon-rich (containing up to 7 wt% C) and were formed early in solar system history, thus the origin of carbon in ureilites has significance for the origin of solar system carbon. These samples were collected soon after they fell, so they among the freshest ureilite samples available and were analyzed using stepped combustion mass spectrometry. They contained 1.2–2.3 wt% carbon; most showed the major carbon release at temperatures of 600–700 °C with peak values of $\delta^{13}\text{C}$ from -7.3 to $+0.4\text{‰}$, similar to literature values for unbrecciated (“monomict”) ureilites. They also contained a minor low temperature (≤ 500 °C) component ($\delta^{13}\text{C} = \text{ca } -25\text{‰}$). Bulk nitrogen contents (9.4–27 ppm) resemble those of unbrecciated ureilites, with major releases mostly occurring at 600–750 °C. A significant lower temperature release of nitrogen occurred in all samples. Main release $\delta^{15}\text{N}$ values of -53 to -94‰ fall within the range reported for diamond separates and acid leached material from ureilites, and identify an isotopically primordial nitrogen component. However, they differ from common polymict ureilites which are more nitrogen-rich and isotopically heavier. Thus, although the parent asteroid 2008TC₃ was undoubtedly a polymict ureilite breccia, this cannot be deduced from an isotopic study of individual ureilite fragments. The combined main release $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values do not overlap the fields for carbonaceous or enstatite chondrites, suggesting that carbon in ureilites was not derived from these sources.

INTRODUCTION

Ureilites are ultramafic achondrite meteorites that are considered to represent the mantle residue of a single parent asteroid body (Takeda 1987; Scott et al. 1993; Goodrich et al. 2004; Downes et al. 2008; Herrin et al. 2010). As such they can be considered as analogues of the early mantle of terrestrial planets. Ureilites are the most carbon-rich of all meteorite types, typically containing 2–7 wt% C (Mittlefehldt et al. 1998; Smith et al. 2001a; Grady and Wright 2003;

Nakamuta 2005). Carbon occurs in ureilites as graphite, diamond and amorphous carbon (Vdovykin 1970; Berkley et al. 1976; Mittlefehldt et al. 1998; Hezel et al. 2008; Le Guillou et al. 2010; Ross et al. 2011a), with other rare carbon polymorphs (El Goresy et al. 2004; Ferroir et al. 2010; Kaliwoda et al. 2011) and carbide phases, e.g., cohenite (Goodrich and Berkley 1986; Warren and Kallemeyn 1994; Goodrich et al. 2013). Other compounds, such as carbonate weathering products (Grady et al. 1985) are likely to represent terrestrial contamination, whereas organic molecules

such as those found by Glavin et al. (2010), Sabbah et al. (2010) and Burton et al. (2011) are thought to be extraterrestrial but unlikely to be derived from the ureilitic precursor.

Despite occasionally occurring in veins (e.g., Corder et al. 2014), ureilitic carbon is usually intergranular and found on grain boundaries. It is considered to be a primary constituent (Berkley and Jones 1982; Rubin 1988) rather than having been introduced late in the formation history of the meteorites. Carbon abundances are commonly higher in ureilites with low core olivine Fo contents (Nakamuta 2005). Diamond in ureilites is usually considered to have formed via shock metamorphism from graphite (Lipschutz 1964; Bischoff et al. 1999; Grund and Bischoff 1999; Nakamuta and Aoki 2000; El Goresy et al. 2004; Fisenko et al. 2004; Hezel et al. 2008; Ross et al. 2011a). However, some studies have suggested that ureilitic diamonds were formed by other processes such as chemical vapor deposition (e.g., Fukunaga et al. 1987; Nagashima et al. 2012; Miyahara et al. 2013).

The first systematic study of carbon isotopes in ureilites was performed by Grady et al. (1985), using a stepped combustion technique on 14 of the 20 ureilites then known, including the only two polymict ureilites known at that time, Nilpena and North Haig. They showed that there is a window between 500 and 800 °C within which graphite/diamond combustion occurs, and suggested that diamond and graphite in ureilites have the same $\delta^{13}\text{C}$ values, but showed that $\delta^{13}\text{C}$ values clearly vary between different ureilites. Later work by Smith et al. (1999, 2001a) showed a somewhat greater range of $\delta^{13}\text{C}$ and carbon contents for a wider variety of ureilite samples. Carbon in ureilites generally has bulk $\delta^{13}\text{C}$ values of -11‰ to 0‰ (Grady et al. 1985; Mittlefehldt et al. 1998; Smith et al. 2001a; Grady and Wright 2003; Hudon et al. 2004). However, $\delta^{13}\text{C}$ values derived by bulk combustion techniques could include a contribution from material released at low temperatures. Consequently, we have applied a stepped heating technique to the Almahata Sitta samples.

Nitrogen is present in ureilites in much lower abundances than carbon (ca 10–150 ppm), but is mostly associated with the carbon phases. Rai et al. (2003) suggested that diamond is the major carrier of nitrogen. Nitrogen is far more complex than carbon in terms of its behavior during stepped combustion. The few nitrogen isotope analyses that have been made of ureilites (Grady et al. 1985; Grady and Pillinger 1988; Russell et al. 1993; Yamamoto et al. 1998; Rai et al. 2002, 2003; Fisenko et al. 2004) have shown that there are multiple nitrogen isotopic components within these meteorites. Rai et al. (2002, 2003) showed that, in contrast to carbon isotopes, $\delta^{15}\text{N}$ values differ between

graphite and diamond in ureilites, with diamond having values of -100‰ and graphite having values of $+19\text{‰}$. Nitrogen in polymict ureilites differs from that in unbrecciated (monomict) ureilites but the paucity of nitrogen isotope data available for polymict ureilites means that only the studies of Grady and Pillinger (1988), Rooke et al. (1998) and Rai et al. (2003) are directly comparable to our investigation. In polymict ureilites, the main nitrogen release occurs below $\sim 600\text{ °C}$ and is isotopically heavy with $\delta^{15}\text{N}$ up to $+530\text{‰}$.

The number of known ureilites has increased greatly in recent years because of numerous finds in both hot and cold deserts. In particular, the 2008 fall of the polymict ureilite Almahata Sitta (Jenniskens et al. 2009; Horstmann and Bischoff 2014) yielded around 600 additional individual stones. These samples are very fresh, thereby minimizing the potential problems with terrestrial weathering reported by Ash and Pillinger (1995). The aim of the current study is to characterize the carbon and nitrogen isotopic values in several ureilitic fragments of Almahata Sitta using a stepped combustion technique that permits simultaneous analysis of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values. Stepped combustion mass spectrometry is a powerful tool for investigating the isotopic composition of carbonaceous components within meteorites (Swart et al. 1983; Wright et al. 1983; Pillinger 1984). Stepped heating allows identification of different carbon phases, and their isotopic compositions, by their characteristic combustion temperatures (Smith et al. 2001a; Grady et al. 2004). However, Smith et al. (2001b) have shown that combustion temperatures of graphite depend to some degree on grain size and crystallinity. Our new data will be compared with literature data for unbrecciated and polymict ureilites in order to assess whether the carbon and nitrogen components in Almahata Sitta samples are similar to, or different from, previously analyzed ureilites. We also aim to determine whether ureilitic carbon was derived from carbonaceous chondrites, as is commonly assumed (e.g., Rubin 1988), and to investigate the variation in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ in the early solar system.

SAMPLES

The meteorites collectively known as Almahata Sitta fell in the Nubian desert of northern Sudan on October 7 2008 (Jenniskens et al. 2009; Jenniskens and Shaddad 2010). The rapid collection of the Almahata Sitta stones means that they can be considered as very fresh samples, having undergone minimal terrestrial weathering through processes such as rainfall. The samples studied in this paper were all recovered during

the first two collecting expeditions in December 2008—less than 3 months after asteroid 2008TC₃ collided with the Earth (Jenniskens et al. 2009; Shaddad et al. 2010). Almahata Sitta has been described as an anomalous polymict (i.e., brecciated) ureilite (Jenniskens et al. 2009). Although not all Almahata Sitta samples have yet been studied, Horstmann and Bischoff (2014) collated the information available for 110 stones, of which 75 are ureilites and 35 are chondrites. This confirms the conclusions of initial mineralogical studies that Almahata Sitta is predominantly ureilitic (Bischoff et al. 2010; Zolensky et al. 2010); ureilites make up 68% of the samples and 73% of the total mass of the stones studied. Of the Almahata Sitta ureilites, just over half (38 samples, ~65% of the ureilite mass (Horstmann and Bischoff 2014)) are coarse-grained akin to the main group of unbrecciated coarse-grained olivine-pyroxene ureilites that have long been dominant in ureilite collections (Goodrich 1992; Mittlefehldt et al. 1998; Goodrich et al. 2004). However, the first sample of Almahata Sitta analyzed (AS7, also studied here) represented a new fine-grained, porous lithology (Jenniskens et al. 2009). An additional 18 samples (making up 25% of ureilite samples but only 9% of the ureilite mass) are similarly anomalous ureilites (Bischoff et al. 2010; Warren and Rubin 2010; Zolensky et al. 2010; Hutchins and Agee 2012; Horstmann and Bischoff 2014).

Four Almahata Sitta chondrites have been analyzed for cosmogenic radionuclides (Bischoff et al. 2010; Meier et al. 2012), three of which are within error of values from the Almahata Sitta ureilites (Welten et al. 2010), indicating that they are all part of the same fall. The abundance of non-ureilitic material has been interpreted to indicate that Almahata Sitta was formed from an asteroid that was dominated by ureilitic material but on which a large proportion of non-indigenous debris had also collected (Horstmann and Bischoff 2014). Almahata Sitta provides important evidence that the source of ureilite meteorites is a brecciated impact-disrupted asteroid (Goodrich et al. 2004; Warren and Huber 2006; Downes et al. 2008; Borovička and Charvát 2009; Herrin et al. 2010).

Estimates of the mass of the 2008TC₃ asteroid before impact vary from 8 t (Kohout et al. 2011) to 108 t (Jenniskens et al. 2009). The combined mass of all Almahata Sitta stones collected to date is approximately 11 kg (Horstmann and Bischoff 2014). Therefore, no matter which calculation of pre-impact mass is used, more than 99% of the original asteroid was lost during the explosions observed as it entered the Earth's atmosphere (Borovička and Charvát 2009; Jenniskens et al. 2009; Jenniskens and Shaddad 2010; Jenniskens

et al. 2010b; Kwok 2009; Jenniskens et al. 2010a; Shaddad et al. 2010). Thus, it is not known to what extent the collected material is representative of the original asteroid.

Five Almahata Sitta stones were selected for analysis (AS7, AS22, AS27, AS36, and AS44). Samples were primarily chosen based on availability of material for destructive analysis, but also cover the range of heterogeneities found within Almahata Sitta. Apart from AS22, the stones studied here have already been investigated by various authors using different techniques. AS7 represents the unusual fine-grained porous lithology and is the same sample initially described from the Almahata Sitta fall and identified as an anomalous ureilite (Jenniskens et al. 2009). The rest are all coarse-grained compact main group ureilites. AS22 and AS427 were large stones (115.32 g and 283.84 g, respectively), whereas AS7 (1.52 g) and AS44 (2.21 g) were much smaller (Shaddad et al. 2010). Three of the samples (AS7, AS36, and AS44) have been described by Zolensky et al. (2010), while samples AS7, AS27, AS36, and AS44 were analyzed by Sandford et al. (2010). AS27 has also been investigated by Warren and Rubin (2010) and Burton et al. (2011) and AS44 was described by Goodrich et al. (2010a). Samples AS36 and AS44 were analyzed by Murty et al. (2010) for nitrogen and noble gases. Among our samples, the presence of diamond has been confirmed by Raman spectroscopy in AS7 (Ross et al. 2011a) and has also been identified in AS22, AS27, and AS44.

The forsterite (Fo) content of olivine cores in previously studied ureilites ranges from ~75 to 96; however, they are not evenly distributed, showing a significant peak at Fo~78–79 with a secondary lesser peak at Fo~90–92 (Goodrich et al. 2004; Downes et al. 2008). Reported Fo values for Almahata Sitta ureilites cover this entire range from Fo~76 to Fo~95 (Bischoff et al. 2010; Warren and Rubin 2010; Kita et al. 2011; Horstmann and Bischoff 2014). Even within this small sample set, there is a major peak at ~Fo79. Oxygen isotope analyses of Almahata Sitta ureilites (Bischoff et al. 2010; Rumble et al. 2010; Kita et al. 2011; Horstmann et al. 2012) also cover the range of values previously found in ureilites (Clayton and Mayeda 1988, 1996; Kita et al. 2004). These data are indicative of the heterogeneity within the original 2008TC₃ asteroid. Our studied samples range in Fo values from 79 (AS44) to 90 (AS36) and their $\Delta^{17}\text{O}$ values range from –0.4 to –1.5‰ (Rumble et al. 2010).

Polished blocks were prepared for petrographic study. AS22 and AS27 were split into petrographic and isotopic sub-samples, with AS36 being already completely disaggregated and requiring no further subdivision. AS7 was provided as two separate pieces,

Table 1. Summary data of C and N in Almahata Sitta samples (see Appendix for full data set). For AS22 N% yield in brackets for main release is value without the release at 1000 °C.

	AS7	AS22	AS27	AS36	AS44
Sample mass (mg)	4.736	5.129	5.466	4.41	4.948
Fo content in olivine	86	80	85	90	79
px*: px/(ol+px) %	0.31	0.28	0.22	0.35	0.15–0.23
Total C (wt%)	1.57	1.18	1.20	2.30	1.88
Carbon					
Average total $\delta^{13}\text{C}$ (‰)	0.0	−7.6	−2.8	−5.4	0.1
Average error (‰)	0.3	0.3	0.3	0.3	0.3
Main release range (° C)	500–700	500–700	500–700	500–700	500–700
C in main release (ng)	70895	58566	58409	91630	84041
C in main release (wt%)	1.49	1.14	1.07	2.06	1.70
% of total C in main release	94.7	96.6	89.3	89.6	90.2
Weighted av $\delta^{13}\text{C}$ in main release ‰	0.4	−7.3	−2.3	−5.2	0.4
Error (‰)	0.3	0.3	0.3	0.3	0.3
Nitrogen					
Total N (ppm)	18.11	27.11	21.19	9.35	11.78
Average total $\delta^{15}\text{N}$ (‰)	−48.2	−29.4	−7.5	−24.1	−52.1
Average error (‰)	0.9	4.5	4.3	2.2	2.4
Main release range (° C)	600–700	600–700	650–700	650–700	600–700
N in main release (ng)	54.63	36.69	34.11	12.41	37.19
N in main release (ppm)	11.47	7.15	6.24	2.79	7.52
% of N in main release	63.3	26.4 (60.5)	29.5	29.9	63.8
Weighted av $\delta^{15}\text{N}$ in main release ‰	−91.0	−69.0	−61.3	−95.6	−94.7
Error (‰)	0.3	4.8	5.3	1.0	1.2

one with fusion crust and one without; the former was made into the polished block and the latter used for isotope analyses. AS44 was provided as two distinct samples, but petrographic and mineralogical analysis of the polished blocks showed them to have identical features and so only one was sub-sampled for isotopic analysis.

The polished blocks of samples studied here are all olivine-dominated (Table 1). When compared with the results from infrared spectroscopy by Sandford et al. (2010), the px* values (where px* = modal px/(modal px + modal ol)) for AS27 are almost identical and our results for AS36 are very close to one of three analyses splits of AS36. However, our sample of AS44 is considerably more olivine-rich and our sample of AS7 is marginally more olivine-rich. All samples contain carbon, with one of the AS44 blocks appearing to contain a vein-like carbon-rich area. The samples also contain metal and sulfide; grain-boundary Fe-metal is the most common form, which can contain minor amounts of Ni and Si and trace amounts of Co and P. AS27 and AS44 both contain carbon-bearing metal phases. In AS27 these are included within silicate grains as “spherules”. In AS44, the C-bearing metal is present in the grain boundaries alongside Fe-metal, schreibersite, and sulfide (Goodrich et al. 2010a; Mikouchi et al. 2011; Agoyagi et al. 2013).

AS7 shows a distinctive porous texture. Olivine core compositions are Fo₈₆. This sample was analyzed by micro Raman techniques (Ross et al. 2011a), which revealed the presence of diamond as well as graphite and amorphous carbon. AS22 has not previously been described. It shows a typical coarse-grained (up to 2 mm) olivine-dominated ureilitic texture with cores of Fo₈₀ (Ross et al. 2011b). Sample AS27 consists of olivine (Fo₈₅) and low-Ca pyroxene. Warren and Rubin (2010) suggested that AS27 may have experienced some degree of shock, resulting in undulose extinction in olivine, and that its original texture may have been poikilitic. Our sample of AS36 was completely disaggregated into individual crystal grains with a small proportion of mixed grains, and therefore it tends to lack interstitial material. It is composed largely of coarse-grained (up to 3 mm) olivine Fo₉₀ crystals (Ross et al. 2011c). AS44 is a coarse-grained (>2 mm) olivine-dominated ureilite (Fo₇₉) with some pigeonite. Its texture resembles those of impact-smelted ureilites (Goodrich et al. 2010a; Ross et al. 2011b).

METHODOLOGY

Almahata Sitta samples were analyzed for C and N abundance and isotopic compositions using a

stepped combustion technique on the FINESSE static vacuum mass spectrometer at the Open University (UK). For detailed information regarding the components and processes within the FINESSE instrument, see Verchovsky et al. (1998, 2002). Care was taken to ensure that no sub-samples used for isotopic analyses had fusion crust attached. The meteorite chips were hand crushed to a powder in a class 10000 clean room, using an agate pestle and mortar. This was transferred to a class 100 clean room where approximately 5 mg of the powdered ureilites were weighed into 0.25 μm thick Pt buckets that had been pre-cleaned by heating to 900 °C in the presence of CuO in a sealed quartz tube pumped to 10^{-7} mbar.

After being loaded in the mass spectrometer extraction system, the samples were heated incrementally from 200 to 1400 °C in the presence of oxygen derived from thermal decomposition, at 930 °C, of CuO present in a separately heated unit with an inlet into the furnace, resulting in the liberation of individual components. Carbon (in the form of CO_2) and molecular nitrogen were cryogenically separated from each other before analysis. Simultaneous analysis was made possible by using multiple mass spectrometers connected to a common extraction line: two magnetic sector mass spectrometers for determination of carbon isotopes and nitrogen abundance, and a quadrupole mass spectrometer for nitrogen isotopes. Abundance yields are recorded in nanograms with errors of <1% in the carbon measurement, made on a capacitance manometer, and <5% in the nitrogen measurements, which were determined from the previously calibrated relationship between $m/z = 28$ intensity and the nitrogen volume. The system blank levels of the instrument are <10 ng and <1 ng for carbon and nitrogen, respectively. Isotopic compositions are reported in the delta (δ) notation as a deviation in parts per thousand (‰) from the Pee Dee Belemnite (vPDB) standard for carbon and from terrestrial air for nitrogen. Isotopic reproducibility is typically <1‰. As a result of the high yields normally found in ureilites (Grady et al. 1985; Smith 2002), blank correction was based on the average yield and isotopic composition of a system blank run prior to the experiment. Total isotopic error was calculated through an error propagation calculation, based on the contribution of the blank to the total yield. Summary results for carbon and nitrogen concentrations and isotopic compositions in the Almahata Sitta samples are given in Table 1, and full results for each temperature step can be found in the Appendix. No N_2 analyses are available for the highest temperature step for AS7 and AS36 because of system failure.

RESULTS

Carbon

In Table 1 we report the average $\delta^{13}\text{C}$ values of the carbon across all temperature ranges (equivalent to the bulk carbon composition), and the weighted average $\delta^{13}\text{C}$ of the carbon released during the temperature steps where >~90% of carbon was liberated (referred to as the “main release carbon”). The main carbon release temperature range is the same in all the samples, occurring between 500 and 700 °C. The total amount of carbon released in all of the samples was 1.18 to 2.3 wt %. The $\delta^{13}\text{C}$ value of the main carbon release is always heavier than that of the total C (Table 1), because of the contribution from an isotopically light, low-temperature component. Differences in $\delta^{13}\text{C}$ between the main release component and the average $\delta^{13}\text{C}$ across all temperatures (i.e., including the low-temperature component) range from 0.2 to 0.5‰.

The five Almahata Sitta ureilite samples have very similar carbon release patterns (Fig. 1). During the steps at <500 °C, less than 2% of the total carbon was released and the $\delta^{13}\text{C}$ values were typically around -25‰. As combustion reached about 600 °C, $\delta^{13}\text{C}$ showed a rapid increase to “peak” (main release) values ranging from -7.3‰ (AS22) to +0.4‰ (AS44). Following the main release of carbon, the samples behaved in slightly different ways. Samples AS7 and AS22 released less than ~4% of their total carbon above 750 °C. The carbon stepped combustion plots (Fig. 1) show that these samples have a very subtle second minor release, at ~900 °C (AS7) and ~1000 °C (AS27). In AS7, the second release is almost identical in isotopic composition to the major release at 650 °C. Thus, the second release probably represents combustion either of higher crystallinity graphite or of genetically related diamond. The latter is more likely as this sample definitely contains diamond (Zolensky et al. 2010; Ross et al. 2011a). Samples AS27, AS36, and AS44 released a slightly larger amount of carbon (~10%) at temperatures >750 °C; the isotopic composition of these releases ranges from +1.5‰ (AS44) to -5.7‰ (AS36). Two of these samples (AS27 and AS44) contain C-rich metal which may account for these high-temperature releases. The extreme change in isotopic composition of the highest temperature release of carbon from AS44 is almost certainly an artifact of the method (possibly furnace residue).

Nitrogen

Table 1 shows the $\delta^{15}\text{N}$ results for the five Almahata Sitta samples; step combustion profiles are

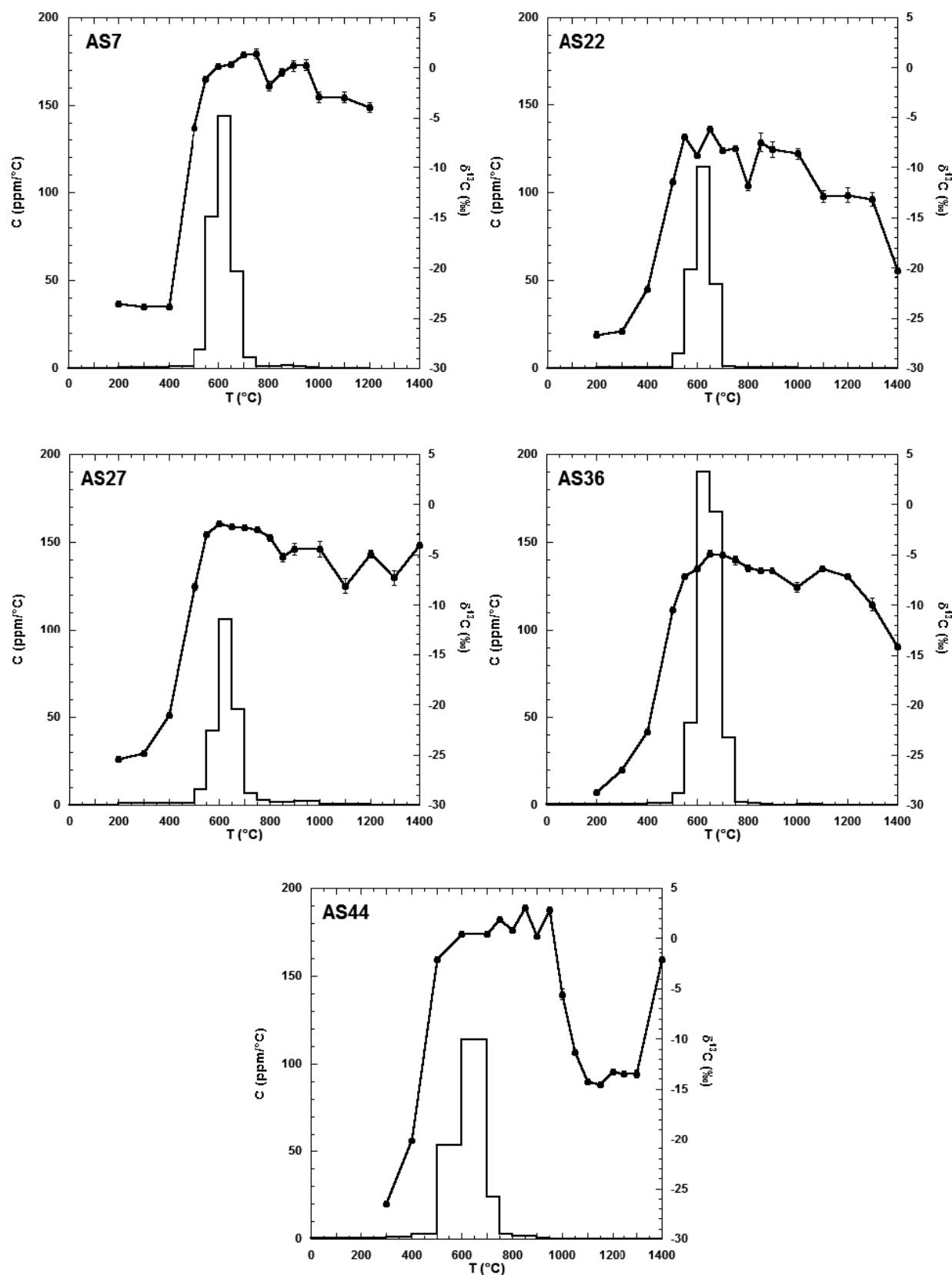


Fig. 1. Carbon release patterns (solid line) and $\delta^{13}\text{C}$ compositions (points with error bars) of five samples of Almahata Sitta ureilites during stepped heating combustion. **8**

shown in Fig. 2. Both the nitrogen abundance combustion profiles and corresponding nitrogen isotopic values show more complexity than for carbon. Nevertheless, all of the samples show a clear main release of nitrogen at around 600–700 °C, over which the $\delta^{15}\text{N}$ values decrease significantly. It is difficult to define the main release peaks because of the presence of lower temperature releases, but in general these main releases yield average $\delta^{15}\text{N}$ values from -61‰ (AS27) to -95.6‰ (AS36). In sample AS22, a second large release peak is seen at a much higher temperature (1000 °C) which lacks these low $\delta^{15}\text{N}$ values.

In contrast to the carbon release profiles, at temperatures below 400°C, up to ~20% of nitrogen was released from all of our samples with a weighted average $\delta^{15}\text{N}$ of +8 to +19‰. Between 400 °C and 600 °C, samples AS7, AS27 and AS36 released 20.8 to 34.5% of total N, with a weighted average $\delta^{15}\text{N}$ of +29 to +42‰. In contrast, samples AS22 and AS44 released less nitrogen (8.7% and 14.0%, respectively) over this temperature range, and this nitrogen was significantly heavier than that seen in the other three samples (+64‰ and +82‰). Sample AS27 was investigated by Burton et al. (2011) who identified the presence of extraterrestrial amino acids. This component may be responsible for the low temperature, heavy nitrogen release.

At temperatures between 600 °C and 900 °C, samples AS7 and AS44 released most (~70%) of their nitrogen. The isotopic composition of this release was the lightest of the analyzed samples in this study, with weighted average $\delta^{15}\text{N}$ values of -84‰ (AS7) and -91‰ (AS44). Samples AS27 and AS36 also released most of their nitrogen over this temperature range, however, it was a much smaller release in terms of total nitrogen (~43%). Its isotopic composition was slightly heavier than that seen in AS7 and AS44, with weighted average $\delta^{15}\text{N}$ values of -40 and -79‰ .

AS22 is unique among the samples in that the 600 °C to 900 °C release only made up 27.8% of total nitrogen, with a $\delta^{15}\text{N}$ of -63‰ . Its largest release (56.4% of total N) occurred at 1000 °C with a corresponding $\delta^{15}\text{N}$ of -29‰ . An extremely similar major release of nitrogen at 1000 °C was reported from Goalpara by Grady et al. (1985). This may suggest an additional, as yet unidentified, component of nitrogen in some ureilites, such as a nitride phase similar to those found in E chondrites. At temperatures >900 °C the other Almahata Sitta ureilite samples released <12% of their total nitrogen with weighted average $\delta^{15}\text{N}$ values in the range -32 to -3‰ . In AS27 and AS36, the nitrogen isotopic composition changed from heavier values to lighter values with increasing temperature. In sample AS44, the opposite pattern was observed,

whereas for AS7, the high-temperature component had a much less variable isotopic composition.

The release patterns of carbon and nitrogen suggest that the two elements are clearly connected, as they are released at similar temperatures (Figs. 1 and 2), although the main release of nitrogen starts at a slightly higher temperature than that of carbon. This may be because the major carrier of nitrogen is diamond which combusts at a slightly higher temperature than graphite. There is a negative correlation between the total amount of carbon released and the total amount of nitrogen released during combustion of the Almahata Sitta samples (Fig. 3a). Sample AS22 represents the sample with the highest nitrogen and lowest carbon abundances (although this value includes the anomalous release of nitrogen at high temperature), whereas sample AS36 represents a low nitrogen, high carbon component (this sample was disaggregated and contains very little interstitial material). A stronger correlation is seen between the total amount of N and the ratio of N/C released from each sample (Fig. 3b). The correlation supports the contention that two separate components dominate the nitrogen isotopes. The nature of these components is discussed below.

DISCUSSION

Comparison of Carbon and Nitrogen With Ureilite Literature Data

The Almahata Sitta ureilite samples show a ubiquitous carbon component at <500 °C which is a very small (<2%) proportion of the total carbon yield and has a $\delta^{13}\text{C}$ value of around -25 to -30‰ (Fig. 1). The low-temperature combustion behavior and isotopic composition of this carbon is suggestive either of terrestrial organic carbon (Hoefs 1997) or of extra-terrestrial, but non-ureilitic, organic components as described by Glavin et al. (2010) and Burton et al. (2011). While these are very minor components in Almahata Sitta samples, these low-temperature components could bias the carbon isotopic value determined from a bulk (i.e., non-stepped combustion) analysis, particularly if the component is terrestrial in origin and the sample has been in the terrestrial environment for a long time.

Data from three older ureilite falls (Dyalpur, Novo-Urei, and Haverö) show a range between 3.6 and 4.7% of total carbon released below 500 °C (Grady et al. 1985), so the Almahata Sitta samples have almost half the abundance of contaminating carbon compared with other falls. For ureilite finds, however, the low-temperature component ranges from 1.7% (Y790981) to 23.7% (Goalpara) of total carbon (Grady et al. 1985).

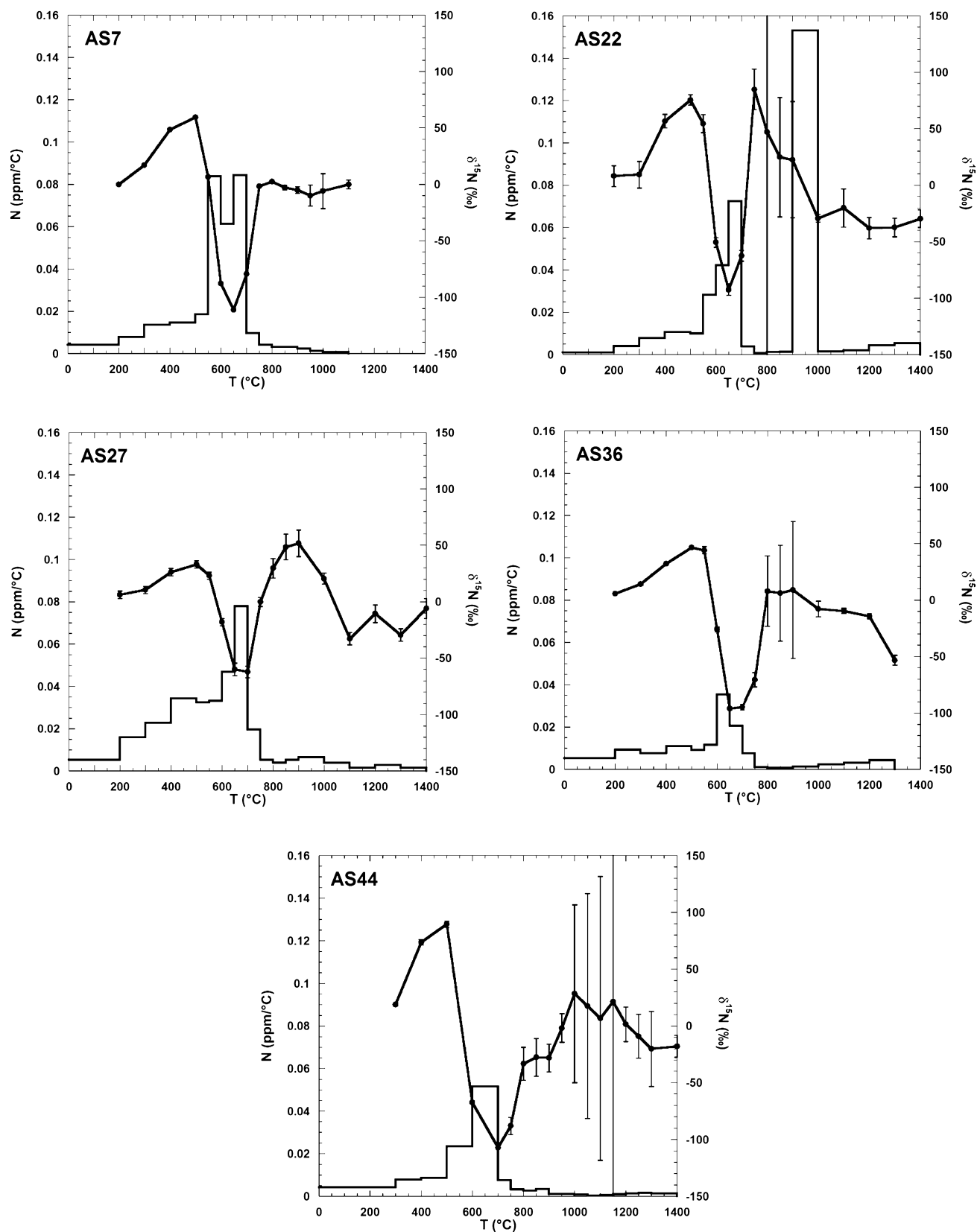
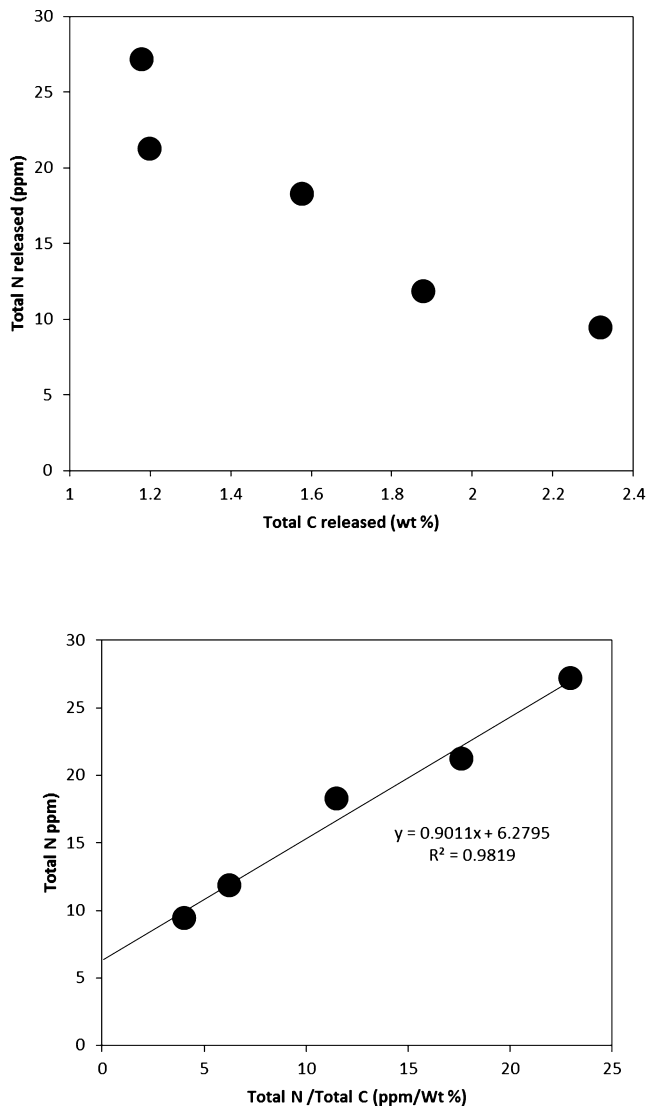


Fig. 2. Nitrogen release patterns (solid line) and nitrogen isotope compositions (points with error bars) of five samples of Almahata Sitta ureilites.



9 Fig. 3. a) Total amount of C versus total amount of N released during stepped combustion of five Almahata Sitta ureilites. b) Total amount of N released versus total N/total C released during stepped combustion of five Almahata Sitta ureilites. N.B. From a mathematical point of view, one of these two correlations cannot be a straight line relationship.

The low-temperature component is also significant in two polymict ureilite samples, North Haig (37.1%) and Nilpena (8.2%). Excluding the anomalously high Goalpara value, and the polymict samples, the low-temperature carbon released by unbrecciated ureilite finds ranges from 1.7% to 6.5%. Thus, in terms of carbon, the Almahata Sitta samples are among the least contaminated ureilites yet studied.

The main carbon components released at higher temperatures are considered to be indigenous ureilitic carbon. Previously analyzed unbrecciated ureilites all have similar ranges in carbon abundance and isotopic

composition (Grady et al. 1985; Smith et al. 2001a; Hudon et al. 2004) and main release $\delta^{13}\text{C}$ values of the Almahata Sitta samples (+0.4 to -7.3‰) fall well within these ranges. Grady et al. (1985) suggested that ureilites show a bimodality of peak $\delta^{13}\text{C}$ values, with clusters around -2‰ and -10‰ . It appeared that the isotopically lighter values were associated with ureilites that had more Mg-rich olivine core compositions ($>\text{Fo}_{83}$), whereas the isotopically heavier values belonged to samples with more Fe-rich ($<\text{Fo}_{80}$) olivine cores (Fig. 4). However, the ureilites studied by Grady et al. (1985) cluster around only two different Fo compositions, although this bias results from the bimodal distribution of core Fo values in all ureilites (Goodrich et al. 2004; Downes et al. 2008). In a later study, Hudon et al. (2004) showed a more extensive data set for both Fo (74–95) and bulk $\delta^{13}\text{C}$ (-11 to $+1\text{‰}$) values that also shows a negative correlation (Fig. 4). The reason for this correlation is not known, although it might relate to mixing of different nebula components in the source of the original UPB. Unlike the data of Grady et al. (1985) and Hudon et al. (2004), our Almahata Sitta ureilite data show no correlation between olivine core Fo composition and $\delta^{13}\text{C}$ values. However, the small number of data points in our study precludes making any conclusion from this observation and, in any case, our data plot in or very near to the field defined by the data of Hudon et al. (2004).

Nitrogen is a trace element in unbrecciated ureilites (3–55 ppm according to Grady and Wright (2003) and Rai et al. (2003)). Our Almahata Sitta ureilite samples yield total nitrogen abundances in the range 9.4–27 ppm, well within this reported range. There are fewer measurements of nitrogen within polymict ureilites but nitrogen yields are generally higher, up to 152 ppm (Grady and Pillinger 1988; Rooke et al. 1998; Rai et al. 2003). Previous stepped combustion studies have suggested multiple components with distinct $\delta^{15}\text{N}$ values with some differences in nitrogen composition and combustion behavior between unbrecciated and polymict ureilites (Grady et al. 1985; Grady and Pillinger 1988; Rooke et al. 1998; Yamamoto et al. 1998; Rai et al. 2003). Grady et al. (1985) measured the abundance and isotopic composition of nitrogen in five ureilite specimens using stepped combustion. Their results showed multiple nitrogen components with different isotopic compositions, released at different temperatures. However, the lightest nitrogen they measured had a $\delta^{15}\text{N}$ value of only -62.4‰ (the 800 °C step in Kenna) and bulk isotopic compositions $\delta^{15}\text{N}$ values ranged from -24.8‰ (Kenna) to $+26.2\text{‰}$ in polymict sample North Haig. For unbrecciated (“monomict”) ureilites, Yamamoto et al. (1998) and Rai et al. (2003) described the main nitrogen release as

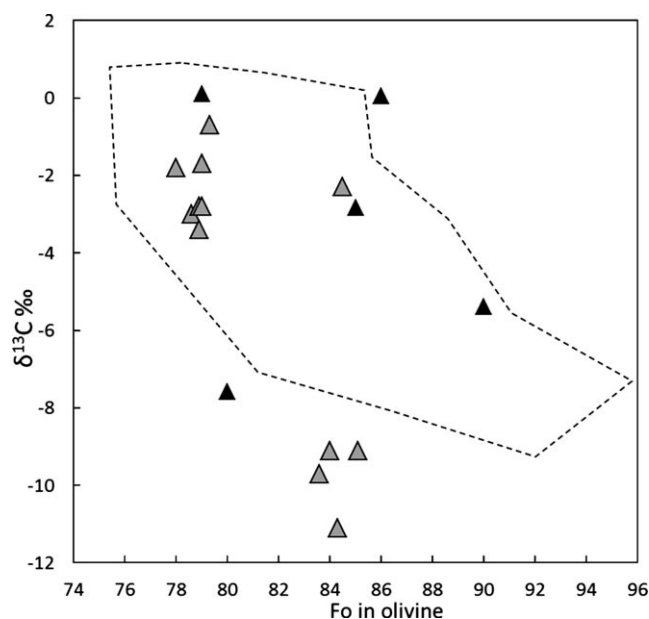


Fig. 4. $\delta^{13}\text{C}$ versus core olivine mg# in analyzed Almahata Sitta ureilites (black triangles) and data for a variety of monomict (unbrecciated) ureilites (gray triangles) analyzed by Grady et al. (1985). Field outlined is for a larger number of unbrecciated ureilites (Hudon et al. 2004).

coinciding with the main carbon release at temperatures between 600 °C and 900 °C, and this nitrogen was isotopically light. The weighted average $\delta^{15}\text{N}$ of the main nitrogen releases have been calculated as -53.6 to -112.4‰ (Yamamoto et al. 1998) and -26.6 to -105‰ (Rai et al. 2003). Unbrecciated ureilites can also contain a significant low temperature, isotopically heavy, component with $\delta^{15}\text{N}$ compositions in the range 0 to $+95\text{‰}$ (Yamamoto et al. 1998; Rai et al. 2003).

Only four polymict ureilites (North Haig, Nilpena, EET 83309, and EET 87720) have been previously analyzed for nitrogen isotopes. Thus, it is difficult to define what the combustion profile of a typical polymict ureilite looks like in comparison with a typical unbrecciated ureilite. However, Grady and Pillinger (1988) identified two components, one isotopically light with $\delta^{15}\text{N}$ values that reached -94‰ and one which is isotopically heavy nitrogen with $\delta^{15}\text{N}$ up to $+600\text{‰}$. All polymict ureilites have a high-yield, low-temperature release (<500 °C) that is isotopically heavy ($\delta^{15}\text{N} \geq +50\text{‰}$ or even $\geq +150\text{‰}$). On the other hand, two combustion profiles of Nilpena show clear evidence for a large release of light nitrogen over temperature intervals of 700–800 °C (weighted average $\delta^{15}\text{N}$ over this temperature range = -66.6‰ ; Grady and Pillinger 1988), and from 700 to 1050 °C ($\delta^{15}\text{N} = -89.5\text{‰}$; Rai et al. 2003).

Our Almahata Sitta results also show ^{15}N enriched values at low temperatures with weighted average

compositions of $+24$ to $+55\text{‰}$ at temperatures between 200 °C and 550 °C, although these values are somewhat less ^{15}N enriched than have been measured previously in polymict ureilites. Their major nitrogen release was over a narrow temperature range within the main carbon release temperature range. Their main release isotopic compositions (from -61‰ to -96‰ ; Table 1) tend to be heavier than the values reported for unbrecciated ureilites by Yamamoto et al. (1998) and Rai et al. (2003). Among our samples, only two (AS7 and AS44) released any nitrogen with a $\delta^{15}\text{N}$ value of $<-100\text{‰}$ and this was only seen in one temperature step in each sample (see Appendix).

Murty et al. (2010) also carried out step-wise combustion analyses of nitrogen isotopes in AS36. Their bulk sample of AS36 contained almost twice the amount of nitrogen (21.1 ppm compared with our value of 9.35 ppm). The main release (63% N) occurred between 800 and 1200 °C, which is much higher than the main release temperature we obtained. However, a very different experimental protocol was used whereby the samples were combusted at 200 °C steps between 300 °C and 1000 °C and then pyrolyzed the sample at 1200 °C, 1400 °C, and 1800 °C, compared with our protocol where the sample was combusted at 50 °C or 100 °C degree steps (combustion involves heating the sample in the presence of oxygen whereas pyrolysis does not). The bulk $\delta^{15}\text{N}$ isotopic composition obtained by Murty et al. (2010) of -36.8‰ is lighter than our bulk value of -24‰ but their peak release, i.e., the single temperature step where the largest amount of N was released, occurred at 1000 °C with a $\delta^{15}\text{N}$ of -94.3‰ , which is within error of the composition (-95.6‰) seen in the 650 °C main release in our analysis of AS36.

In a stepped combustion study of carbon-bearing acid residues and diamond concentrates from ureilites, Russell et al. (1993) showed that $\delta^{15}\text{N}$ values reach -100 to -120‰ at temperatures >600 °C, whereas at low temperatures the isotopic composition was $\sim 0\text{‰}$. Fisenko et al. (2004) obtained $\delta^{15}\text{N}$ values for acid residue samples of Novo-Urei (the oldest ureilite fall and the meteorite that gives the ureilites their name) of -108‰ and -114‰ . Murty et al. (2010) also analyzed an acid residue sample from AS44 using stepped combustion, in which the major release occurred at temperatures ≥ 600 °C with corresponding $\delta^{15}\text{N}$ values ranging from -96.0‰ to -115.3‰ , very similar to our main release value of -94.7‰ for this sample.

For nitrogen, any terrestrial atmospheric contamination would be expected to be most apparent in the steps below 500 °C, although Hashizume and Sugiura (1995) describe terrestrial nitrogen as being detectable at temperatures up to 700 °C in ordinary chondrites. Nitrogen stepped combustion data are

available for three ureilite falls: Dyalpur (Grady et al. 1985), Lahrauli and Haverö (Rai et al. 2003). The low-temperature nitrogen abundance ranges from 19.5% (Dyalpur; Grady et al. 1985) to 38.5% (Haverö; Rai et al. 2003). For unbrecciated ureilite finds, the nitrogen abundance at <500 °C is highly variable and ranges from 11.2% to 65.9% of total nitrogen (Grady et al. 1985; Yamamoto et al. 1998; Rai et al. 2003). The Almahata Sitta samples yield 5–30% of total nitrogen at <500 °C and so, on the basis of abundance alone, it is not obvious that they show less terrestrial nitrogen contamination than other ureilites. Atmospheric nitrogen adsorbed by interaction with the terrestrial environment would push the $\delta^{15}\text{N}$ values toward 0‰, whereas terrestrial biological nitrogen has $\delta^{15}\text{N}$ values from +5.1‰ to +10.2‰ (Boyd et al. 1993), which would also cause a similar trend to higher values if the samples had been contaminated by biological material. However, it is difficult to ascertain the contribution of contaminating terrestrial nitrogen by looking at the isotopic composition at these temperatures as at least some of this low-temperature component is probably indigenous nitrogen. This contribution may be from extraterrestrial but non-ureilitic organic material (Glavin et al. 2010; Burton et al. 2011) that has been found in Almahata Sitta ureilites and which would combust in this temperature range. Acapulcoites and lodranites have recently been shown to contain a similar extraterrestrial organic component (Charon et al. 2014).

C & N in the Solar System

Figure 5 compares our carbon and nitrogen isotope results with literature values for different groups of carbonaceous chondrites and enstatite chondrites. Two sets of results are shown for the Almahata Sitta ureilitic fragments: one set (open symbols) shows the bulk release of carbon and nitrogen whereas the second set (closed symbols) shows the isotopic composition for the main release (Table 1). Two of our samples (AS7 and AS44) are almost indistinguishable on this plot, despite having different olivine core compositions and different textural characteristics. All of our data fall outside the fields of known carbonaceous chondrites (Fig. 5). We therefore suggest that, despite the well-known similarity of oxygen isotopes between ureilites and carbonaceous chondrites (Clayton and Mayeda 1988), on the basis of carbon and nitrogen isotopes, we agree with Grady et al. (1985) and Smith (2002) that it is unlikely that ureilites were formed from a carbonaceous chondritic precursor. This conclusion is also in agreement with that of Warren (2011) based on non-traditional stable isotope ratios. Data for acid residues and diamond concentrates from ureilites (Russell et al. 1993; Fisenko

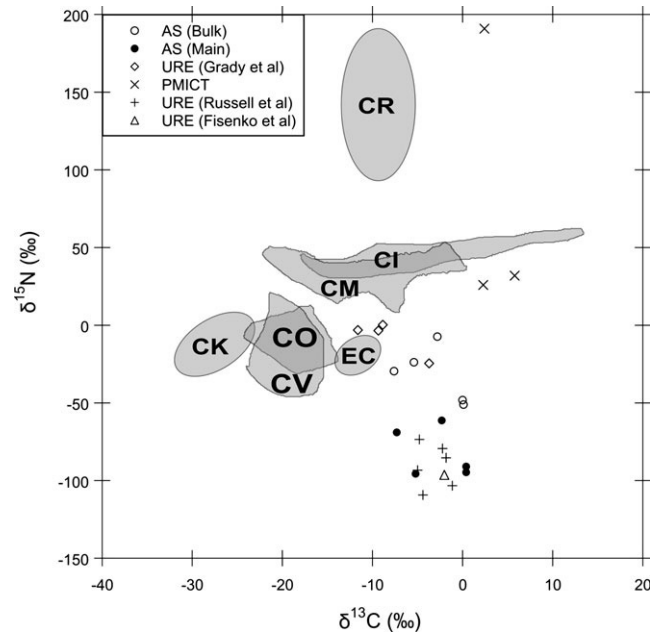


Fig. 5. Comparison of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in the Almahata Sitta ureilites with literature data from other ureilites and carbonaceous and enstatite chondrites (data from Kerridge 1985; Grady et al. 1986; Sephton et al. 2003; Pearson et al. 2006). Almahata Sitta data are shown as “Bulk” (average isotopic composition of total carbon and nitrogen, Table 1) and “Main” (weighted average isotopic composition taken from the main release temperature range, Table 1). “Ure (Russell et al.)” are acid-treated ureilites (Russell et al. 1993), “Ure (Fisenko et al.)” are ureilite diamond separates (Fisenko et al. 2004), averaged across the whole combustion range.

et al. 2004), in which the low-temperature N-isotope component has been removed, overlap the main release data for AS7, AS44, and AS36 (Fig. 5) and point toward a primordial component.

Objects within the solar system vary in their carbon isotope ratios because of three processes: (1) fractionation of carbon isotopes by nebula condensation; (2) the presence of unequilibrated carbon-rich presolar grains (e.g., SiC, diamond); and (3) fractionation effects related to secondary processes on the parent body, e.g., aqueous alteration, thermal metamorphism and shock. There is very little possibility of the presence of presolar grains in the Almahata Sitta samples, as a result of the extensive processing ureilites have experienced (although any presolar grains that may have been present might have been reworked and their carbon liberated during parent body processing). Furthermore, although ureilites display ample evidence for shock, there is no obvious difference between highly shocked and low shock ureilites in terms of carbon isotopes. Therefore, the range in $\delta^{13}\text{C}$ observed in ureilites is most probably a result of variations within the primordial solar nebula. An alternative process,

isotopic fractionation during redox reactions on the original ureilite parent asteroid, is considered to be unlikely according to the results of a study of Smith et al. (2000a).

The origin and extent of variation in N-isotopes in the solar system are not well understood (Aleon 2010; Marty et al. 2011). Nitrogen isotopic variation is generally considered to have been produced by mixing between isotopically light primordial solar nitrogen ($\delta^{15}\text{N} = -380\text{‰}$) and an isotopically heavy (up to $+4000\text{‰}$) component. The latter seems to be formed by isotope fractionation processes such as a self-shielding effect (Clayton 2002) or ion-molecular reactions from solar nitrogen (Franchi et al. 1986). Some solar system objects contain a high fraction of solar nitrogen, e.g., osbornite in CAIs have $\delta^{15}\text{N} = -360\text{‰}$ (Meibom et al. 2007) whereas iron meteorites have $\delta^{15}\text{N} = -96\text{‰}$ (Franchi et al. 1993). A diamond-bearing extraterrestrial pebble found in the Libyan desert also yields $\delta^{15}\text{N}$ values of -100‰ (Marty et al. 2014). Ureilites formed early in solar system history (no later than 4564 Ma, according to Goodrich et al. (2010b) and Qin et al. (2010)) and contain a significant fraction of light nitrogen. Acapulcoites also show a similar component with even lighter nitrogen of $\delta^{15}\text{N} = -150\text{‰}$ (El Goresy et al. 2005). This suggests that nitrogen-bearing carbonaceous material was formed very early in the solar system and escaped significant processing in the ureilite parent body. Terrestrial diamonds generally have $\delta^{15}\text{N}$ values of -5‰ and the lightest values found for Earth ($\delta^{15}\text{N} = -39\text{‰}$) occur very rarely (Palot et al. 2012). Thus, Earth may also retain a very small remnant of primordial nitrogen.

Nature of Almahata Sitta Parent Asteroid

One of the puzzling issues with regards to the origin and history of the asteroid from which the Almahata Sitta samples were derived is the similarities and differences with samples traditionally described and classified as polymict ureilites (i.e., brecciated and with inhomogeneous olivine core compositions) and those described as monomict ureilites (i.e., those that are unbrecciated and have homogeneous olivine core compositions). Previous investigations of polymict ureilites suggested that, because of the presence of a wide-variety of exotic components such as carbonaceous chondrite-like dark clasts (Brearley and Prinz 1992) and other chondritic (OC, EC, RC) and angritic clasts (Ikeda et al. 2003; Goodrich et al. 2004; Kita et al. 2004; Downes et al. 2008), these meteorites originated as regolith materials on the ureilite daughter asteroidal body. Such regolith breccias also show evidence for solar wind implantation (Ott et al. 1990).

In terms of the mineralogy and petrography of the Almahata Sitta samples studied here, the individual fragments are unbrecciated lithologies, displaying dominant olivine and pyroxene with abundances and compositions similar to those found within the range of unbrecciated ureilites. However, the abundance of non-ureilitic stones found within the strewn field clearly indicates that the Almahata Sitta parent body was extremely heterogeneous in its composition and was undoubtedly a brecciated asteroid (Herrin et al. 2010; Bischoff et al. 2010). However, despite knowing that Almahata Sitta was a polymict breccia, the carbon and nitrogen results from the ureilitic fragments do not suggest the presence of any non-ureilitic material, other than perhaps the high- T ($\sim 1000\text{ °C}$) nitrogen component in AS22. It is therefore possible that other areas where ureilite finds are common (e.g., Dar al Gani; Frontier Mountains) may be relics of unrecognized previous falls of polymict ureilites (Smith et al. 2001b; Downes et al. 2010).

CONCLUSIONS

1. Ureilite fragments from the Almahata Sitta fall are not unusual in their C isotopes; the $\delta^{13}\text{C}$ results obtained for their main carbon release ($+0.4$ to -7.3‰) fall within the same range as those previously analyzed in unbrecciated ureilites. However, they are somewhat anomalous in that they have low carbon contents ($<2.5\text{ wt\% C}$) and do not clearly lie on a trend of Fo in olivine cores versus $\delta^{13}\text{C}$ in carbon (Fig. 4).
2. Bulk carbon and nitrogen analyses of ureilite meteorites always include an isotopically light component which may be terrestrial in origin, even when freshly collected like those from Almahata Sitta. Stepped combustion analyses can help compensate for this and produce more accurate values for the indigenous light isotope component in meteorites. In terms of C abundance and isotopes, the Almahata Sitta samples are some of the least contaminated.
3. Although derived from a polymict ureilite breccia, the analyzed Almahata Sitta ureilite fragments more closely resemble unbrecciated (monomict) ureilites, rather than polymict ones, in terms of their carbon and nitrogen abundances and isotopic compositions. They are missing the low- T , very heavy N component seen in other polymict ureilites. Thus, they do not represent the surficial regolith from which other polymict ureilites are considered to originate. A ubiquitous low- T high N/C component may be related to the presence of non-indigenous extraterrestrial organic material.

4. Three of the Almahata Sitta ureilites show main release $\delta^{15}\text{N}$ values that are around -90‰ , similar to the values for acid residues and diamond concentrates from ureilites. On a diagram of $\delta^{15}\text{N}$ vs $\delta^{13}\text{C}$, the Almahata Sitta ureilites do not overlap the fields of any of the carbonaceous or enstatite chondrites, and hence ureilitic carbon was not derived from these sources but shows evidence for a primordial nebula origin.

Acknowledgments—FAJA acknowledges the receipt of an STFC PhD studentship. AJR acknowledges the receipt of a NERC (UK) studentship award through UCL and CASE support from the NHM. We are grateful to Mike Zolensky (JSC, NASA) for providing the Almahata Sitta #7 sample. We greatly appreciate the helpful and constructive reviews of Dominik Hezel, Matthias Maier, Cyrena Goodrich, and an anonymous reviewer.

Editorial Handling—Dr. Cyrena Goodrich

REFERENCES

- Agoyagi Y., Mikouchi T., and Goodrich C. A. 2013. New observations on grain boundary metal in ureilitic fragments of Almahata Sitta (abstract #1448). 44th Lunar and Planetary Science Conference. CD-ROM.
- Aleón J. 2010. Multiple origins of nitrogen isotopic anomalies in meteorites and comets. *The Astrophysical Journal* 722:1342–1351.
- Ash R. D. and Pillinger C. T. 1995. Carbon, nitrogen and hydrogen in Saharan chondrites: The importance of weathering. *Meteoritics* 30:85–92.
- Berkley J. L. and Jones J. H. 1982. Primary igneous carbon in ureilites: Petrological implications. *Journal of Geophysical Research Supplement* 87:353–364.
- Berkley J. L., Brown H. G., and Keil K. 1976. The Kenna ureilite: An ultramafic rock with evidence for igneous, metamorphic, and shock origin. *Geochimica et Cosmochimica Acta* 40:1429–1430.
- Bischoff A., Goodrich C. A., and Grund T. 1999. Shock-induced origin of diamonds in ureilites (abstract #1100). 30th Lunar and Planetary Science Conference. CD-ROM.
- Bischoff A., Horstmann M., Pack A., Laubenstein M., and Haberer S. 2010. Asteroid 2008TC₃—Almahata Sitta: A spectacular breccia containing many different ureilitic and chondritic lithologies. *Meteoritics & Planetary Science* 45:1638–1656.
- Borovička J. and Charvát Z. 2009. Meteosat observation of the atmospheric entry of 2008 TC₃ over Sudan and the associated dust cloud. *Astronomy & Astrophysics* 507:1015–1022.
- Boyd S. R., Hall A., and Pillinger C. 1993. The measurement of $\delta^{15}\text{N}$ in crustal rocks by static vacuum mass spectrometry: Application to the origin of the ammonium in the Cornubian batholith, southwest England. *Geochimica et Cosmochimica Acta* 57:1339–1347.
- Brearley A. J. and Prinz M. 1992. CI chondrite-like clasts in the Nilpena polymict ureilite—Implications for aqueous alteration processes in CI chondrites. *Geochimica et Cosmochimica Acta* 56:1373–1386.
- Burton A. S., Glavin D. P., Callahan M. P., Dworkin J. P., Jenniskens P., and Shaddad M. H. 2011. Heterogeneous distributions of amino acids provide evidence of multiple sources within the Almahata Sitta parent body, asteroid 2008 TC₃. *Meteoritics & Planetary Science* 46:1703–1712.
- Charon E., Aléon J., and Rouzaud J.-N. 2014. Impact delivery of organic matter on the acapulcoite-lodranite parent-body deduced from C, N isotopes and nanostructures of carbon phases in Acapulco and Lodran. *Geochimica et Cosmochimica Acta* 142:224–239.
- Clayton R. N. 2002. Solar system: Self-shielding in the solar nebula. *Nature* 415:860–861.
- Clayton R. N. and Mayeda T. K. 1988. Formation of ureilites by nebula processes. *Geochimica et Cosmochimica Acta* 52:1313–1318.
- Clayton R. N. and Mayeda T. K. 1996. Oxygen isotope studies of achondrites. *Geochimica et Cosmochimica Acta* 60:1999–2017.
- Corder C. A., Day J. M. D., Rumble D., Assayag N., Cartigny P., and Taylor L. A. 2014. A carbon-rich region in ureilite Miller Range 091004 (abstract #1777). 45th Lunar and Planetary Science Conference. CD-ROM.
- Downes H., Mittlefehldt D. W., Kita N. T., and Valley J. W. 2008. Evidence from polymict ureilite meteorites for a disrupted and re-accreted single ureilite parent asteroid gardened by several distinct impactors. *Geochimica et Cosmochimica Acta* 72:4825–4844.
- Downes H., Ross A. J., and Smith C. L. 2010. Ureilite meteorites from Dar al Gani (Libya) and Frontier Mountains (Antarctica): Analogues of the Almahata Sitta (Asteroid 2008 TC₃) fall? (abstract #5106). 73rd Annual Meteoritical Society.
- El Goresy A., Gillet P., Dubrovinsky L., Chen M., and Nakamura T. 2004. A super-hard, transparent carbon form, diamond and secondary graphite in the Haverö ureilite: A fine-scale microRaman and synchrotron tomography (abstract #5061). 67th Annual Meteoritical Society Meeting.
- El Goresy A., Zinner E., Pellas P., and Caillet C. 2005. A menagerie of graphite morphologies in the Acapulco meteorite with diverse carbon and nitrogen isotopic signatures: Implications for the evolution history of acapulcoite meteorites. *Geochimica et Cosmochimica Acta* 69:4535–4556.
- Ferroir T., Dubrovinsky L., El Goresy A., Nakamura T., and Gillet P. 2010. Carbon polymorphism in shocked meteorites: Evidence for new natural ultrahard phases. *Earth & Planetary Science Letters* 290:150–154.
- Fisenko A. V., Verchovsky A. B., Semjonova L. F., and Pillinger C. T. 2004. Carbon, nitrogen and noble gases in the diamond fractions of the Novo Urei ureilite. *Solar System Research* 38:383–393.
- Franchi I. A., Wright I. P., and Pillinger C. T. 1986. Heavy nitrogen in Bencubbin—Light element isotopic anomaly in a stony-iron meteorite. *Nature* 323:138–140.
- Franchi I. A., Wright I. P., and Pillinger C. T. 1993. Constrains on the formation of iron meteorites based on concentration and isotopic compositions of nitrogen. *Geochimica et Cosmochimica Acta* 57:3105–3121.
- Fukunaga K., Matsuda J., Nagao K., Miyamoto M., and Ito K. 1987. Noble-gas enrichment in vapour-growth diamonds and the origin of diamonds in ureilites. *Nature* 328:141–143.

- Glavin D. P., Aubrey A. D., Callahan M. P., Dworkin J. P., Elsila J. E., Parker E. T., Bada J. L., Jenniskens P., and Shaddad M. H. 2010. Extraterrestrial amino acids in the Almahata Sitta meteorite. *Meteoritics & Planetary Science* 45:1695–1709.
- Goodrich C. A. 1992. Ureilites: A critical review. *Meteoritics* 27:327–352.
- Goodrich C. A. and Berkley J. 1986. Primary magmatic carbon in ureilites: Evidence from cohenite-bearing metallic spherules. *Geochimica et Cosmochimica Acta* 50:681–691.
- Goodrich C. A., Scott E. R. D., and Fioretti A. M. 2004. Ureilitic breccias: Clues to the petrological structure and impact disruption of the ureilite parent asteroid. *Chemie der Erde* 64:283–327.
- Goodrich C. A., Goldstein J., Kita N. T., Mikouchi M., Zolensky M., Herrin J., Ash R. D., McDonough W. F., and Jenniskens P. 2010a. Metal in ureilitic fragments of Almahata Sitta (abstract #5319). 73rd Annual Meeting of the Meteoritical Society.
- Goodrich C. A., Hutcheon I. D., Kita N. T., Huss G. R., Cohen B. A., and Keil K. 2010b. ^{53}Mn - ^{53}Cr and ^{26}Al - ^{26}Mg ages of a feldspathic lithology in polymict ureilites. *Earth and Planetary Science Letters* 295:531–540.
- Goodrich C. A., Ash R. D., Van Orman J. A., Domanik K., and McDonough W. F. 2013. Metallic phases and siderophile elements in main group ureilites: Implications for ureilite petrogenesis. *Geochimica et Cosmochimica Acta* 112:340–373.
- Grady M. M. and Pillinger C. T. 1988. ^{15}N -enriched nitrogen in polymict ureilites and its bearing on their formation. *Nature* 331:321–323.
- Grady M. M. and Wright I. P. 2003. Elemental and isotopic abundances of carbon and nitrogen in meteorites. *Space Science Reviews* 106:231–248.
- Grady M. M., Wright I. P., Swart P. K., and Pillinger C. T. 1985. The carbon and nitrogen isotopic composition of ureilites. Implications for their genesis. *Geochimica et Cosmochimica Acta* 49:903–915.
- Grady M. M., Wright I. P., Carr L. P., and Pillinger C. T. 1986. Compositional differences in enstatite chondrites based on carbon and nitrogen stable isotope measurements. *Geochimica et Cosmochimica Acta* 50:2799–2813.
- Grady M. M., Verchovsky A. B., and Wright I. P. 2004. Magmatic carbon in Martian meteorites: Attempts to constrain the carbon cycle on Mars. *International Journal of Astrobiology* 3:117–124.
- Grund T. and Bischoff A. 1999. Cathodoluminescence properties of diamonds in ureilites: Further evidence for a shock-induced origin. *Meteoritics & Planetary Science* 34 (Supplement):A48.
- Hashizume K. and Sugiura N. 1995. Nitrogen isotopes in bulk ordinary chondrites. *Geochimica et Cosmochimica Acta* 59:4057–4069.
- Herrin J. S., Zolensky M. E., Ito M., Le L., Mittlefehldt D. W., Jenniskens P., Ross A. J., and Shaddad M. H. 2010. Thermal and fragmentation history of ureilitic asteroids: Insights from the Almahata Sitta fall. *Meteoritics & Planetary Science* 45:1789–1803.
- Hezel D. C., Dubrovinsky L., Nasdala L., Cauzid J., Simionovici A., Gellissen M., and Schoenbeck T. 2008. In situ micro-Raman and X-ray diffraction study of diamonds and petrology of the new ureilite UAS 001 from the United Arab Emirates. *Meteoritics & Planetary Science* 43:1127–1136.
- Hoefs J. 1997. *Stable isotope geochemistry*. London: Springer.
- Horstmann M. and Bischoff A. 2014. The Almahata Sitta polymict breccia and the late accretion of asteroid 2008TC₃. *Chemie der Erde – Geochemistry* 74:149–183.
- Horstmann M., Bischoff A., Pack A., Albrecht N., Weyrauch M., Hain H., Roggon L., and Schnieder K. 2012. Mineralogy and oxygen isotope composition of new samples from the Almahata Sitta strewn field (abstract #5052). 75th Annual Meeting of the Meteoritical Society.
- Hudon P., Romanek C., Paddock L., and Mittlefehldt D. W. 2004. Evolution of the ureilite parent body (abstract #2075). 35th Lunar and Planetary Science Conference. CD-ROM.
- Hutchins K. I. and Agee C. B. 2012. Microprobe analyses of two Almahata Sitta ureilites (abstract #2435). 43rd Lunar and Planetary Science Conference. CD-ROM.
- Ikeda Y., Kita N. T., Morishita Y., and Weisberg M. K. 2003. Primitive clasts in the Dar al Gani 319 polymict ureilite: Precursors of the ureilites. *Antarctic and Meteorite Research* 16:105–127.
- Jenniskens P., Shaddad M. H., Numan D., Elsir S., Kudoda A. M., Zolensky M. E., Le L., Robinson G. A., Friedrich J. M., Rumble D., Steele A., Chesley S. R., Fitzsimmons A., Duddy S., Hsieh H. H., Ramsay G., Brown P. G., Edwards W. N., Tagliaferri E., Boslough M. B., Spalding R. E., Dantowitz R., Kozubal M., Pravec P., Borovicka J., Charvat Z., Vaubaillon J., Kuiper J., Albers J., Bishop J. L., Mancinelli R. L., Sandford S. A., Milam S. N., Nuevo M., and Worden S. P. 2009. The impact and recovery of asteroid 2008 TC₃. *Nature* 458:485–488.
- Jenniskens P. and Shaddad M. H. 2010. 2008TC₃: The small asteroid with an impact. *Meteoritics & Planetary Science* 45:1553–1556.
- Jenniskens P., Shaddad M. H., and the Almahata Sitta Consortium. 2010a. The unusually frail asteroid 2008TC₃. *Proceedings of the International Astronomical Union* 5: 227–230.
- Jenniskens P., Vaubaillon J., Binzel R. P., DeMeo F. E., Nesvorný D., Bottke W. F. R., Fitzsimmons A., Hiroi T., Marchis F., Bishop J. L., Vernazza P., Zolensky M. E., Herrin J. S., Welten K. C., Meier M. M. M., and Shaddad M. H. 2010b. Almahata Sitta (= asteroid 2008 TC₃) and the search for the ureilite parent body. *Meteoritics & Planetary Science* 45:1–28.
- Kaliwoda M., Hoffmann V. H., Hochleitner R., Mikouchi T., and Gigler A. 2011. New Raman spectroscopic data of Almahata Sitta (abstract #2225). 42nd Lunar and Planetary Science Conference. CD-ROM.
- Kerridge J. F. 1985. Carbon, hydrogen and nitrogen in carbonaceous chondrites: Abundances and isotopic compositions in bulk samples. *Geochimica et Cosmochimica Acta* 49:1707–1714.
- Kita N. T., Ikeda Y., Togashi S., Liu Y., Morishita Y., and Weisberg M. K. 2004. Origin of ureilites inferred from as SIMS oxygen isotopic and trace element study of clasts in the Dar al Gani 319 polymict ureilite. *Geochimica et Cosmochimica Acta* 68:4213–4235.
- Kita N. T., Goodrich C. A., Zolensky M. E., Herrin J. S., Shaddad M. H., and Jenniskens P. 2011. Oxygen isotope systematics of Almahata Sitta (abstract #1491). 42nd Lunar and Planetary Science Conference. CD-ROM.
- Kohout T., Kiuru M., Montonen P., Britt D., Macke R., and Consolmagno G. 2011. Internal structure and physical

- properties of the Asteroid 2008TC₃ inferred from a study of the Almahata Sitta meteorites. *Icarus* 212:697–700.
- Kwok R. 2009. The rock that fell to Earth. *Nature* 458:401–403.
- Le Guillou C., Rouzaud J. N., Remusat L., Jambon A., and Bourot-Denise M. 2010. Structures, origin and evolution of various carbon phases in the ureilite Northwest Africa 4742 compared with laboratory-shocked graphite. *Geochimica et Cosmochimica Acta* 74:4167–4185.
- Lipschutz M. E. 1964. Origin of diamonds in ureilites. *Science* 143:1431–1434.
- Marty B., Chaussidon M., Wiens R. C., Jurewicz A. J. G., and Burnett D. S. 2011. A ¹⁵N-poor isotopic composition for the solar system as shown by Genesis Solar Wind samples. *Science* 332:1533–1536.
- Marty B., Zimmermann L., Meier M. M., Avice G., Kramers J. D., Andreoli M. A. G., Cartigny P., and Wieler R. 2014. Nitrogen, neon and argon isotopes in Hypatia, a diamond bearing pebble from the Lybien desert glass strewnfield. 77th Annual Meteoritical Society Meeting.
- Meibom A., Krot A. N., Robert F., Mostefaoui S., Russell S. S., Petaev M. I., and Gounelle M. 2007. Nitrogen and carbon isotopic composition of the Sun inferred from a high-temperature solar nebular condensate. *The Astrophysical Journal* 656:L33–L36.
- Meier M. M. M., Welten K. C., Caffee M. W., Friedrich J. M., Jenniskens P., Nishiizumi K., Shaddad M. H., and Weiler R. 2012. A noble gas and cosmogenic radionuclide analysis of two ordinary chondrites from Almahata Sitta. *Meteoritics & Planetary Science* 47:1075–1086.
- Mikouchi T., Goodrich C. A., Hoffman V. H., Zolensky M. E., and Sugiyama K. 2011. Electron back-scatter diffraction study of iron metal in Almahata Sitta ureilite (abstract #5409). 74th Annual Meeting Meteoritical Society.
- Mittlefehldt D. W., McCoy T. J., Goodrich C. A., and Kracher A. 1998. Non-chondritic meteorites from asteroidal bodies. In *Planetary materials*, edited by Papike J. J. Washington, D.C.: Mineralogical Society of America. pp. 4-01–4-175.
- Miyahara M., Ohtani E., El Goresy A., Lin Y. T., Feng L., Zhang J. C., Gillet P., Nagase T., Muto J., and Nisijima M. 2013. A huge single diamond in Almahata Sitta coarse-grained ureilite (abstract #1719). 44th Lunar and Planetary Science Conference. CD-ROM.
- Murty S. V. S., Mahajan R. R., Jenniskens P., Shaddad M. H., and Eldin B. 2010. Noble gases and nitrogen in the Almahata Sitta ureilite. *Meteoritics & Planetary Science* 45:1751–1764.
- Nagashima K., Nara M., and Matsuda J. 2012. Raman spectroscopic study of diamond and graphite in ureilites and the origin of diamonds. *Meteoritics & Planetary Science* 47:1728–1737.
- Nakamuta Y. 2005. Modal abundances of carbon in ureilites: Implications for the petrogenesis of ureilites (abstract #1089). 36th Lunar and Planetary Science Conference. CD-ROM.
- Nakamuta Y. and Aoki Y. 2000. Mineralogical evidence for the origin of diamond in ureilites. *Meteoritics & Planetary Science* 35:487–493.
- Ott U., Löhr H. P., and Begemann F. 1990. EET 83309: A ureilite with solar noble gases. *Meteoritics* 29:396.
- Palot M., Cartigny P., Harris J. W., Kaminsky F. V., and Stachel T. 2012. Evidence for deep mantle convection and primordial heterogeneity from nitrogen and carbon stable isotopes in diamond. *Earth and Planetary Science Letters* 357–358:179–193.
- Pearson V. K., Sephton M. A., Franchi I. A., Gibson J. M., and Gilmour I. 2006. Carbon and nitrogen in carbonaceous chondrites: Elemental abundances and stable isotopic compositions. *Meteoritics & Planetary Science* 41:1899–1918.
- Pillinger C. T. 1984. Light stable isotopes in meteorites—From grams to picograms. *Geochimica et Cosmochimica Acta* 48:2739–2766.
- Qin L., Rumble D., Alexander C. M. O'D., Carlson R. W., Jenniskens P., and Shaddad M. H. 2010. The chromium isotopic composition of Almahata Sitta. *Meteoritics & Planetary Science* 45:1771–1777.
- Rai V. K., Murty S. V. S., and Ott U. 2002. Nitrogen in diamond-free ureilite Allan Hills 78019: Clues to the origin of diamonds in ureilites. *Meteoritics & Planetary Science* 37:1045–1055.
- Rai V. K., Murty S. V. S., and Ott U. 2003. Nitrogen components in ureilites. *Geochimica et Cosmochimica Acta* 67:2213–2237.
- Rooke G. P., Franchi I. A., Verchovsky A. B., and Pillinger C. T. 1998. The relationship between noble gases and the heavy nitrogen in polymict ureilites (abstract #1744). 29th Lunar and Planetary Science Conference. CD-ROM.
- Ross A. J., Steele A., Fries M. D., Kater L., Downes H., Jones A. P., Smith C. L., Jenniskens P. M., Zolensky M. E., and Shaddad M. H. 2011a. MicroRaman spectroscopy of diamond and graphite in Almahata Sitta and comparison with other meteorites. *Meteoritics & Planetary Science* 46:364–378.
- Ross A. J., Herrin J. S., Mittlefehldt D. W., Downes H., Smith C. L., Lee M. R., Jones A. P., Jenniskens P., and Shaddad M. H. 2011b. Petrography and geochemistry of metals in Almahata Sitta ureilites (abstract #2720). 42nd Lunar and Planetary Science Conference. CD-ROM.
- Ross A. J., Hezel D. C., Howard L. E., Smith C. L., Downes H., Herrin J. S., Jenniskens P., and Shaddad M. 2011c. Petrography and modal abundance of metals in ureilites: A combined 2D and 3D study (abstract #5193). 74th Annual Meteoritical Society Meeting.
- Rubin A. E. 1988. Formation of ureilites by impact-melting of carbonaceous chondritic material. *Meteoritics* 23:333–337.
- Rumble D., Zolensky M. E., Friedrich J. M., Jenniskens P., and Shaddad M. H. 2010. The oxygen isotope composition of Almahata Sitta. *Meteoritics & Planetary Science* 45:1765–1770.
- Russell S. S., Arden J. W. E., Franchi I. A., and Pillinger C. T. 1993. A carbon and nitrogen isotope study of carbonaceous vein material in ureilite meteorites (abstract). 24th Lunar and Planetary Science Conference. p. 1221.
- Sabbah H., Morrow A. L., Jenniskens P., Shaddad M. H., and Zare R. N. 2010. Polycyclic aromatic hydrocarbons in asteroid 2008 TC₃: Dispersion of organic compounds inside asteroids. *Meteoritics & Planetary Science* 45:1710–1717.
- Sandford S. A., Milam S. N., Nuevo M., Jenniskens P., and Shaddad M. H. 2010. The mid-infrared transmission spectra of multiple stones from the Almahata Sitta meteorite. *Meteoritics & Planetary Science* 45:1821–1835.
- Scott E. R. D., Taylor G. J., and Keil K. 1993. Origin of ureilite meteorites and implications for planetary accretion. *Geophysical Research Letters* 20:415–418.
- Sephton M. A., Verchovsky A. B., Bland P. A., Gilmour I., Grady M. M., and Wright I. P. 2003. Investigating the variations in carbon and nitrogen isotopes in carbonaceous chondrites. *Geochimica et Cosmochimica Acta* 67(11):2093–2108.

- Shaddad M. H., Jenniskens P., Numan D., Kudoda A. M., Elsir S., Riyad I. F., Ali A. E., Alameen M., Alameen N. M., Eid O., Osman A. T., Abubaker M. I., Yousif M., Chesley S. R., Chodas P. W., Albers J., Edwards W. N., Brown P. G., Kuiper J., and Friedrich J. M. 2010. The recovery of asteroid 2008 TC₃. *Meteoritics & Planetary Science* 45:1557–1589.
- Smith C. L. 2002. An integrated mineralogical, petrologic and isotopic study of ureilites. PhD Thesis, Open University.
- Smith C. L., Franchi I. A., Wright I. P., Grady M. M., Verchovsky A. B., and Pillinger C. T. 1999. A preliminary noble gas and light-element stable isotopic study of the Frontier Mountain 90228 low-carbon ureilite. *Meteoritics & Planetary Science Supplement* 34:110.
- Smith C. L., Franchi I. A., Wright I. P., Grady M. M., and Pillinger C. T. 2000a. Disko island C-rich basalts: A terrestrial analogue for ureilite petrogenesis and their carbon isotope systematics (abstract #1735). 31st Lunar and Planetary Science Conference. CD-ROM.
- Smith C. L., Wright I. P., Franchi I. A., and Grady M. M. 2000b. A statistical analysis of mineralogical data from Frontier Mountain ureilites. *Meteoritics & Planetary Science Supplement* 35:A150.
- Smith C. L., Franchi I., Wright I., Grady M., and Pillinger C. T. 2001a. New data on carbon isotopic compositions of some ureilites (abstract #1878). 32nd Lunar and Planetary Science Conference. CD-ROM.
- Smith C. L., Franchi I. A., Wright I. P., Grady M. M., and Pillinger C. T. 2001b. Ureilitic graphite: Shocking implications. *Meteoritics & Planetary Science Supplement* 36:A193.
- Swart P., Grady M., and Pillinger C. 1983. A method for the identification and elimination of contamination during carbon isotopic analyses of extraterrestrial samples. *Meteoritics & Planetary Science* 18:137–154.
- Takeda H. 1987. Mineralogy of Antarctic ureilites and a working hypothesis for their origin and evolution. *Earth & Planetary Science Letters* 81:358–370.
- Vdovykin G. P. 1970. Ureilites. *Space Science Reviews* 10:483–510.
- Verchovsky A. B., Fisenko A. V., Semjonova L. F., Wright I. P., Lee M. R., and Pillinger C. T. 1998. C, N and noble gas isotopes in grain size separates of presolar diamonds from Efremovka. *Science* 281:1165–1168.
- Verchovsky A. B., Sephton M. A., Wright I. P., and Pillinger C. T. 2002. Separation of planetary noble gas carrier from bulk carbon in enstatite chondrites during stepped combustion. *Earth & Planetary Science Letters* 199:243–255.
- Warren P. H. 2011. Stable isotopes and the non-carbonaceous derivation of ureilites, in common with nearly all differentiated planetary materials. *Geochimica et Cosmochimica Acta* 75:6912–6926.
- Warren P. H. and Huber H. 2006. Ureilite petrogenesis: A limited role for smelting during anatexis and catastrophic disruption. *Meteoritics & Planetary Science* 41:835–849.
- Warren P. H. and Kallemeyn G. W. 1994. Petrology of LEW88774: An extremely chromium-rich ureilite (abstract). 25th Lunar and Planetary Science Conference. p. 1465.
- Warren P. H. and Rubin A. E. 2010. Pyroxene-selective impact smelting in ureilites. *Geochimica et Cosmochimica Acta* 74:5109–5133.
- Welten K. C., Meier M. M. M., Caffee M. W., Nishiizumi K., Weier R., Jenniskens P., and Shaddad M. H. 2010. Cosmogenic nuclides in Almahata Sitta ureilites: Cosmic-ray exposure age, pre-atmospheric mass, and bulk density of asteroid 2008TC₃. *Meteoritics & Planetary Science* 45:1728–1742.
- Wright I. P., McNaughton N. J., Fallick A. E., Gardiner L. R., and Pillinger C. T. 1983. A high-precision mass spectrometer for stable carbon isotope analysis at the nanogram level. *Journal of Physics E: Scientific Instruments* 16:497–504.
- Yamamoto T., Hasizume K., Matsuda J., and Kase T. 1998. Multiple nitrogen isotopic components coexisting in ureilites. *Meteoritics & Planetary Science* 33:857–870.
- Zolensky M., Herrin J., Mikouchi T., Ohsumi K., Friedrich J., Steele A., Rumble D., Fries M., Sandford S., Milam S., Hagiya K., Takeda H., Satake W., Kurihara T., Colbert M., Hamna R., Maisano J., Ketcham R., Goodrich C., Le L., Robinson G.-A., Martinez J., Ross K., Jenniskens P., and Shaddad M. H. 2010. Mineralogy and petrography of the Almahata Sitta ureilite. *Meteoritics & Planetary Science* 45:1618–1637.

APPENDIX

Table A1. Full data set of stepped combustion analyses of five ureilitic fragments from Almahata Sitta.

Sample	Temperature (°C)	Carbon yield (ng)	Carbon yield (ppm/°C)	$\delta^{13}\text{C}$ (‰)	\pm	Nitrogen yield (ng)	Nitrogen yield (ppm/°C)	$\delta^{15}\text{N}$ (‰)	\pm
AS7	200	259.71	0.27	-23.53	0.26	4.02	0.00	-0.08	0.27
	300	322.40	0.68	-23.90	0.27	3.73	0.01	17.11	0.50
	400	369.99	0.78	-23.87	0.28	6.53	0.01	48.53	0.67
	500	420.29	0.89	-5.98	0.27	6.98	0.01	59.59	0.75
	550	2570.06	10.85	-1.17	0.29	4.46	0.02	6.61	0.30
	600	20508.76	86.61	0.18	0.30	19.94	0.08	-88.02	0.40
	650	34261.67	144.69	0.29	0.00	14.61	0.06	-111.08	0.50
	700	13134.67	55.47	1.30	0.26	20.08	0.08	-79.30	0.32
	750	1460.37	6.17	1.39	0.46	2.30	0.01	-1.68	0.39
	800	292.59	1.24	-1.79	0.49	0.98	0.00	2.49	0.81
	850	331.60	1.40	-0.41	0.39	0.76	0.00	-2.94	2.03
	900	385.75	1.63	0.21	0.55	0.74	0.00	-5.03	3.07
	950	283.25	1.20	0.25	0.54	0.54	0.00	-9.84	9.30
	1000	151.84	0.64	-2.91	0.54	0.32	0.00	-5.97	15.50
AS22	1100	55.53	0.12	-2.94	0.53	0.28	0.00	0.00	3.82
	1200	62.65	0.13	-3.93	0.48				
	200	270.61	0.26	-26.65	0.35	1.10	0.00	8.06	9.24
	300	170.82	0.33	-26.29	0.19	2.04	0.00	9.41	11.79
	400	172.77	0.34	-22.08	0.16	4.00	0.01	56.76	6.10
	500	356.96	0.70	-11.46	0.16	5.53	0.01	75.49	4.48
	550	2089.76	8.15	-6.96	0.16	2.55	0.01	54.50	7.92
	600	14398.76	56.15	-8.80	0.17	7.24	0.03	-50.68	4.15
	650	29421.67	114.73	-6.20	0.24	10.84	0.04	-92.43	5.02
	700	12298.67	47.96	-8.27	0.00	18.60	0.07	-62.49	4.91
	750	316.11	1.23	-8.09	0.23	1.01	0.00	84.84	17.98
	800	125.64	0.49	-11.83	0.44	0.22	0.00	47.03	203.03
	850	156.98	0.61	-7.51	0.91	0.33	0.00	24.79	52.85
	900	175.86	0.69	-8.21	0.75	0.35	0.00	22.57	51.32
AS27	1000	238.73	0.47	-8.64	0.54	78.45	0.15	-29.27	3.32
	1100	119.57	0.23	-12.85	0.60	0.81	0.00	-20.18	16.81
	1200	85.48	0.17	-12.76	0.71	1.00	0.00	-37.98	9.38
	1300	117.88	0.23	-13.20	0.66	2.26	0.00	-37.30	8.23
	1400	103.22	0.20	-20.27	0.59	2.71	0.01	-29.61	7.83
	200	286.66	0.26	-25.46	0.17	5.78	0.01	6.18	3.36
	300	484.57	0.89	-24.82	0.19	8.67	0.02	10.56	3.22
	400	519.72	0.95	-21.03	0.23	12.39	0.02	26.25	3.31
	500	693.43	1.27	-8.16	0.30	18.71	0.03	33.22	3.27
	550	2367.46	8.66	-2.95	0.25	8.84	0.03	23.23	3.17
	600	11554.76	42.28	-1.85	0.25	9.07	0.03	-17.94	3.22
	650	28952.67	105.94	-2.20	0.00	12.80	0.05	-59.93	5.45
	700	14840.67	54.30	-2.33	0.00	21.30	0.08	-62.18	5.14
	750	1770.77	6.48	-2.51	0.23	5.32	0.02	-0.15	3.89
	800	775.35	2.84	-3.31	0.32	1.45	0.01	29.73	8.71
	850	510.96	1.87	-5.24	0.45	1.10	0.00	48.63	11.47
	900	532.36	1.95	-4.41	0.55	1.44	0.01	51.77	11.76
	1000	1149.65	2.10	-4.43	0.79	3.56	0.01	20.62	4.88
	1100	455.96	0.83	-8.09	0.71	2.16	0.00	-32.81	5.51
	1200	270.67	0.50	-4.89	0.38	0.81	0.00	-10.53	7.81
	1300	122.01	0.22	-7.25	0.73	1.57	0.00	-29.44	5.54

Table A1. *Continued.* Full data set of stepped combustion analyses of five ureilitic fragments from Almahata Sitta.

Sample	Temperature (°C)	Carbon yield (ng)	Carbon yield (ppm/°C)	$\delta^{13}\text{C}$ (‰)	\pm	Nitrogen yield (ng)	Nitrogen yield (ppm/°C)	$\delta^{15}\text{N}$ (‰)	\pm
AS36	1400	133.68	0.24	-4.05	1.16	0.86	0.00	-5.95	8.85
	200	299.16	0.34	-28.73	0.18	4.76	0.01	5.62	0.95
	300	356.50	0.81	-26.54	0.17	4.09	0.01	14.13	1.09
	400	278.69	0.63	-22.70	0.20	3.44	0.01	32.40	1.42
	500	415.63	0.94	-10.42	0.18	4.93	0.01	46.69	1.26
	550	1544.86	7.01	-7.13	0.23	2.03	0.01	44.22	3.16
	600	10339.76	46.89	-6.38	0.19	2.58	0.01	-25.85	1.82
	650	42181.67	191.30	-4.88	0.36	7.85	0.04	-96.12	1.28
	700	37147.67	168.47	-5.00	0.00	4.55	0.02	-94.77	2.32
	750	8491.17	38.51	-5.54	0.42	1.68	0.01	-70.49	6.33
	800	410.69	1.86	-6.32	0.31	0.23	0.00	7.98	31.07
	850	227.31	1.03	-6.52	0.24	0.17	0.00	6.22	42.41
	900	88.39	0.40	-6.56	0.28	0.17	0.00	8.93	60.59
	1000	126.29	0.29	-8.19	0.47	0.58	0.00	-7.81	7.03
	1100	170.93	0.39	-6.35	0.25	1.07	0.00	-9.55	2.41
	1200	99.39	0.23	-7.11	0.22	1.43	0.00	-14.19	2.20
	1300	54.28	0.12	-9.94	0.61	1.95	0.00	-53.29	4.31
AS44	1400	17.56	0.04	-14.17	0.26				
	300	912.56	0.61	-26.54	0.13	6.13	0.00	18.79	1.44
	400	505.72	1.02	-20.21	0.21	3.89	0.01	73.75	2.40
	500	1292.42	2.61	-2.09	0.18	4.25	0.01	89.62	2.63
	600	26498.76	53.55	0.40	0.00	11.64	0.02	-67.32	1.46
	700	56249.76	113.68	0.43	0.16	25.55	0.05	-107.11	1.17
	750	5880.36	23.77	1.94	0.23	1.85	0.01	-87.99	7.39
	800	629.40	2.54	0.81	0.19	0.83	0.00	-33.25	14.66
	850	482.77	1.95	3.03	0.25	0.69	0.00	-27.60	16.67
	900	380.67	1.54	0.25	0.18	0.84	0.00	-28.12	12.18
	950	106.41	0.43	2.82	0.30	0.28	0.00	-1.83	12.59
	1000	49.51	0.20	-5.55	0.53	0.28	0.00	28.36	78.27
	1050	30.21	0.12	-11.28	0.29	0.19	0.00	17.45	99.01
	1100	17.39	0.07	-14.23	0.32	0.10	0.00	6.71	125.02
	1150	22.89	0.09	-14.56	0.33	0.15	0.00	21.47	180.95
	1200	22.54	0.09	-13.27	0.29	0.22	0.00	1.55	15.22
	1250	24.30	0.10	-13.48	0.31	0.33	0.00	-9.00	19.39
	1300	30.44	0.12	-13.49	0.44	0.37	0.00	-20.14	33.05
	1400	57.24	0.12	-2.06	0.69	0.72	0.00	-17.97	9.65